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Direct observations of fish incapacitation rates at a large electrical fish barrier in the Chicago Sanitary and Ship Canal

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ABSTRACT

The electric barrier system in the Chicago Sanitary and Ship Canal was designed to eliminate interbasin transfer of aquatic nuisance species between the Mississippi River and Great Lakes Basins. Electrical output was recently increased in an effort to more effectively eliminate the upstream migration of bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*). Using gizzard shad (*Dorosoma cepedianum*) as a surrogate species, we examined the effectiveness of the barrier at incapacitating fish by placing them in a non-conductive cage and transporting the fish through the barrier. This experiment was conducted before and after changes in operating parameters. Higher electrical output increased barrier effectiveness by decreasing the distance required to incapacitation. Overall, 97% and 100% of fish became incapacitated at the lower and higher electrical operating parameters, respectively. Fish were incapacitated the soonest during the winter and spring, which was likely influenced by the reduced movement activity in the cooler months and the larger fish available for testing later in the spring. Moreover, effectiveness was influenced by type of boat hull material used during testing. Fish that were transported through the barrier along an aluminum-hull boat were able to swim nearly twice the distance into the barrier as those transported with a fiberglass-hull boat during the summer. The delayed incapacitations along the aluminum boat were presumably due to distortion of the electrical field caused by the conductive hull. These results raise concerns regarding the effect that metal-hull barges might have on the effectiveness of the barrier during navigation.

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Introduction

The Laurentian Great Lakes Basin has a long history of exotic species introductions (Mills et al., 1966; Holeck et al., 2004). Additional, potential invaders of concern, namely bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*), are well established in the nearby Mississippi River Basin. These two species are of particular concern to fisheries managers because of their rapid population growth and planktivorous feeding, which may compete with native larval fishes and adult filter-feeding fishes (Chick and Pegg, 2001; Schrank et al., 2003; Irons et al., 2007; Cooke and Hill, 2010). These fish also have the potential to negatively affect a $7 billion per year fishing industry in the Great Lakes (Buck et al., 2010).

The Chicago Area Waterway System (CAWS; Fig. 1) is a network of canals and heavily-modified rivers that artificially link the Great Lakes and Mississippi River Basins that can serve as a conduit for interbasin, invasive species exchange (Jerde et al., 2011). In 1990, the U.S. Congress authorized the U.S. Army Corps of Engineers (USACE) to study non-physical barriers in the CAWS in an effort to prevent the invasion of the non-native round goby (*Neogobius melanostomus*) into the Mississippi River Basin (Sparks et al., 2010). Based on factors such as cost, success likelihood, environmental impact, commercial availability, permit requirements, and effects on existing uses of the CAWS, an electrical barrier was recommended as the best option as a non-physical fish barrier (Moy et al., 2010).

In April 2002, an electric Demonstration Barrier was activated in the Chicago Sanitary and Ship Canal (CSSC), yet, downstream dispersal of round goby had occurred six years prior to its construction (Steingraeber and Thiel, 2000; Sparks et al., 2010). This electrical barrier system, the largest in the world, is much different than any other past or present electrical barriers in several respects, and it has been expanded greatly since its original construction (described below). The section of

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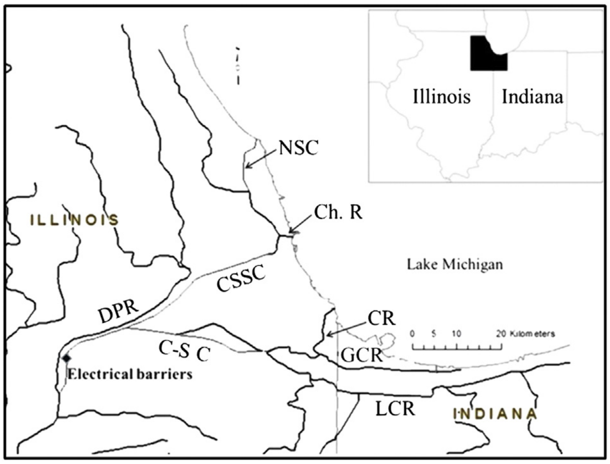

Fig. 1. Chicago Area Waterway System, important tributaries and canals, as well as the location of electrical barriers indicated by the black diamond. CR = Calumet River, C-S C = Cal.-Sag Canal, Ch. R = Chicago River, CSSC = Chicago Sanitary and Ship Canal, DPR = Des Plaines River, GCR = Grand Calumet River, LCR = Little Calumet River, NSC = North Shore Canal.

the CSSC where the barriers are located, near Romeoville, Illinois, is 57-m wide and 7.7-m deep; flow and conductivity fluctuate greatly throughout the year, and the canal is actively used for commercial and recreational vessel navigation (Moy et al., 2010; Sparks et al., 2010).

Despite being constructed post-invasion of round goby, the electric barrier system is still being used as a primary barrier to interbasin transfer of aquatic nuisance species in general. The effectiveness of electrical fish barriers has been evaluated in controlled laboratory and field settings (Barwick and Miller, 1996; Savino et al., 2001; Dawson et al, 2006; Holliman, 2011) and at smaller permanent barrier locations in small streams and canals that do not facilitate navigation (Swink, 1999; Verrill and Berry, 1995; Maceina et al., 1999; Clarkson, 2004). Effectiveness of electrical barriers in controlled laboratory settings were evaluated via direct observation. Studies in field settings relied on indirect assessment methods such as mark–recapture, and telemetry, as well as sampling above the barrier for the targeted species. Although the barriers in the abovementioned studies were largely effective, only Maceina et al. (1999) found their electric barrier to be 100% effective at inhibiting the movement of the targeted fish. Causes of barrier breach in other studies included persistent challenging of the barrier by the fish (Barwick and Miller, 1996; Savino et al., 2001; Dawson et al., 2006; Holliman, 2011), increased water flows (Verrill and Berry, 1995), or unknown causes (Swink, 1999). Clarkson (2004) extensively documented numerous problems that arose at a barrier in an Arizona canal, mainly power outages, that resulted in grass carp (*Ctenopharyngodon idella*) breach of the barrier.

The first studies to directly test the effectiveness of the Demonstration Barrier in the CSSC were by Dettmers et al. (2005) and Sparks et al. (2010). Dettmers et al. (2005) passed encaged fish (Catostomidae spp., *Morone* spp., and common carp [*Cyprinus carpio*]) through the Demonstration Barrier alongside metal-hull barges and fiberglass boats, finding that some fish that were towed along the metal-hulled barges were never incapacitated as they swam through the barrier. Dettmers et al. (2005) attributed the delayed and non-incapacitations to a distortion of the electrical field by the barges. The fiberglass boats did not cause any electrical distortion and all fish that were moved alongside it were incapacitated (Dettmers et al., 2005). Sparks et al. (2010) released 130 common carp with surgically-implanted, combined radio-and-acoustic transmitters downstream of the barrier. One fish was able to breach the barrier, which was later determined to have coincided with the passage of a barge through the barrier. This gave rise to the hypothesis that either (a) the fish was involuntarily entrained by the barge or (b) the barge distorted the electrical field, allowing the fish to swim alongside the barge in an electrical void (Sparks et al., 2010).

Shortly after the fish breach was recorded by Sparks et al. (2010), the operating parameters of the Demonstration Barrier was increased from 2 ms, 2 Hz, < 0.39 V/cm to 4 ms, 5 Hz, and 0.39 V/cm (0.39 V/cm). Following the Dettmers et al. (2005) study, design modifications were implemented to account for the barge-induced electrical distortion to two additional electrical barriers slated for construction. These barriers, Barriers IIA and IIB, began operating in 2009 and 2011 respectively. The newer barriers cover a much larger area than the Demonstration Barrier and are capable of generating electrical fields of much higher intensity. The two barriers consist of two downstream, wide arrays that emit a weak electrical field and two upstream, narrow arrays that emit the maximum target voltage. Parasitic structures are in place above and below the main barrier arrays to contain all "stray" electricity within the barrier system (Table 1; Holliman, 2011). The purpose of this gradual increase in voltage, moving from downstream to upstream, is for fish to slowly encounter increasing electricity. This allows them to alter their behavior before encountering a narrow, high voltage field meant to incapacitate them. Having only a narrow, high voltage field could induce a panic response in which the fish could continue to swim farther into the barrier until it breaches the barrier under its own momentum (Hartley and Simpson, 1967).

After the completion of Barrier IIA in 2009, additional field testing was performed by Sass and Ruebush (2010). Sass and Ruebush (2010) placed a wide variety of fish directly in the strongest part of the barrier and found that all fish were incapacitated when operating parameters were increased to 6.5 ms, 15 Hz, and 0.79 V/cm. The operating parameters of Barrier IIA were increased to 0.79 V/cm in August 2009 and later increased to 2.5 ms, 30 Hz, and 0.91 V/cm as a result of laboratory work with silver and bighead carps (Holliman, 2011). Holliman (2011) found that 0.91 V/cm incapacitated 100% of small bighead carp that were exposed to gradual increases in voltage in a swim tunnel. However, those parameters were only about 90% effective at preventing fish from swimming through an electrical barrier in a flowing raceway that small bighead carp were allowed to challenge.

The behavior of fish that encounter electrical barriers has been described in both laboratory (McMillan, 1928; Hadderingh and Jansen, 1990; Savino et al., 2001; Dawson et al., 2006; Holliman, 2011) and controlled field settings (Stewart, 1981; Barwick and Miller, 1996). We are only aware of one other study (Sass and Ruebush, 2010) that directly observed fish behavior in the new, larger barriers within the CSSC. Sass and Ruebush (2010) evaluated whether fish would become incapacitated or not by immediately placing the fish into the strongest part of the barrier system. However, they did not investigate the distance in which fish could potentially penetrate the barrier, which could have strong implications for maintenance operations in which barriers are switched from one to the other such that fish could swim

Table 1
Description of caged-fish observation points. For visual representation refer to Fig. 2.

Site number	Description
Site 1	Area downstream of all electrical structures where water-borne electricity is typically minimal.
Site 2	Area immediately downstream of the downstream operating parasitic structure where water-borne electricity is typically minimal.
Site 3	Middle of downstream operating, downstream parasitic structure
Site 4	Area immediately downstream of the downstream operating wide-array, low-field structure
Site 5	Area immediately downstream of the second electrode bank of the wide-array structure
Site 6	Area between the two narrow, high-field arrays where voltage is typically highest.
Site 7	Middle of first operating, upstream parasitic structure
Site 8	Area upstream of all barrier structures where voltage is typically minimal.

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through the barrier system (at least once per year, electrical and mechanical components of the barrier must be inspected and cleaned; to ensure the safety of inspectors, the barrier must be de-energized [Matthew Shanks, USACE-Chicago, per. Comm.]). The effect of the canal wall or different navigation vessel hulls on the shape and strength of the barrier's electric field as well as their indirect effects on fish ability to swim through the barrier were unknown for Barriers IIA and IIB.

We evaluated the behavior of caged fish that were physically transported through Barriers IIA or IIB. Our specific objectives were to evaluate the distances that fish were able to swim into Barriers IIA and IIB at the reduced and current operating parameters. We evaluated the probability of incapacitation for caged fish that were moved through the barriers, during different seasons, in different canal locations (mid-channel or near a canal wall), and with boats of differing hull conductivity. Initial caged-fish work consisted of using only an aluminum-hull boat. However, later a fiberglass-hull boat also was used to contrast the effect that a metal-hull boat had on the barrier's electrical field and whether fish behavior was affected by any potential field distortion.

Gizzard shad (*Dorosoma cepedianum*) was used as a surrogate species to emulate small Asian carp attempting to traverse the barrier. Asian carp were not used in the caged-fish trials because of escapement concerns. The gizzard shad was chosen as a surrogate species because its body morphology and habitat preferences are similar to Asian carp and shad was locally abundant in the CSSC so as to minimize potential collection handling stress. Recent work comparing the susceptibility of small Asian carp and gizzard shad to electricity has revealed that outcomes of electrical exposures applied in a scaled-model of the barriers showed induction of passage-preventing behaviors (e.g. immobility, incapacitation) at any given time in the simulations were significantly greater in bighead and silver carps compared to similar sizes of gizzard shad (F. Michael Holliman, Fish Research and Development LLC, Per. Comm.). Therefore, our results using gizzard shad may over-estimate the distances that Asian carp could penetrate the barrier.

Methods

Study species

Gizzard shad that were used in the caged-fish trials were collected via cast netting during fall 2011 and winter 2011. Later, when fish became more difficult to locate, we collected gizzard shad via electrofishing for the remainder of the trials. All fish were collected on the same day that the trials took place. The gizzard shad were held in an oval-shaped holding tank with pure oxygen diffused into it. The circular tank allowed them to continuously swim around the tank unimpeded and greatly reduced their holding stress. Although collection of the gizzard shad used in the trials was random in nature, large fish (>300 mm TL) were not targeted. The current barrier operating parameters are based on the immobilization potential for bighead carp ranging in size from 46–82 mm TL (Holliman, 2011). Because of the small size of the bighead carp that were used by Holliman (2011), the smallest fish available were used since small fish are thought to pose the greatest risk for barrier breach (Holliman, 2011; Parker et al., 2013). Temperature (°C) and conductivity (mS/cm) were recorded during each trial run at a stationary location using a Hydrolab (OTT Hydromet, Loveland, CO) water quality sonde.

Data collection

The cage used in the trials had a non-conductive PVC frame (160-cm L × 58-cm W × 89-cm D) with 0.95-cm bar monofilament mesh. The cage was secured alongside a boat using custom mounts. During the first evaluation in the summer of 2011, a dual-frequency identification sonar (DIDSON; Sound Metrics Corp., Bellevue, WA) unit, mounted on the opposite side of the boat, was used to record fish behavior in the cage. The DIDSON software can process up to seven frames per second, so rather than an acoustic "still" image, DIDSON provides near-video-quality real-time imaging (Moursund et al., 2003). However, after the first evaluation with the DIDSON unit, we found that water clarity and visibility allowed us to record fish behavior with a camcorder mounted above the cage. Using a camcorder allowed for faster set up time in the field and allowed for easier navigation of the boat without the DIDSON in the water. Later comparisons of camcorder and DIDSON recordings revealed no differences in reviewer's ability to interpret fish behavior.

Five gizzard shad were randomly netted out of the holding tank, placed in the cage, and moved through one of the following three 115-m sections of the CSSC moving from south to north (upstream): (a) through the mid-channel of the CSSC over the entire array of electrical barrier structures, (b) along the western canal wall of the CSSC, over the entire array of electrical barrier structures, or (c) a control area through the mid-channel of the CSSC, in non-electrified water (Fig. 2). The upstream end of the control trial run was approximately 100-m downstream of all electrical barrier structures and outside of any electrical influences. For the runs that were performed through the barrier

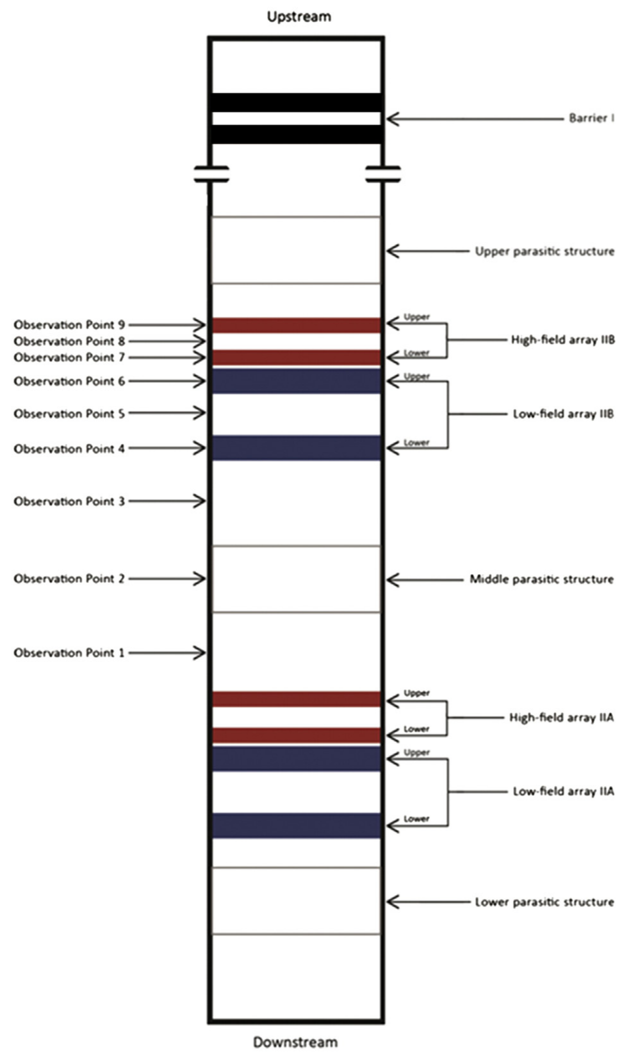

Fig. 2. Schematic of the trial observation points and barrier arrays within the CSSC where caged-fish were moved from downstream to upstream. Observation points used in the control runs were the same distances apart but downstream of the barrier area in an un-electrified zone. Observation points indicate where behaviors were later recorded. Note: drawing is not to scale and represents caged-fish observation points if only Barrier IIB was operating. Blue color represents low-field wide arrays, red color represents high-field narrow arrays, and black represents Barrier 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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system, the starting point was in an area of non-electrified water. Ten trial runs were performed within each section of the canal per experimental event. The order in which the trial runs took place in the different locations was generated with a random-number generator. After each trial run, the fish were measured (mm; TL) and released alive (i.e. different fish were used in each trial run). Measurements were made post-trial run to reduce handling stress. Individual fish were not given unique identifiers (e.g. external tags).

Our evaluations were performed in either Barrier IIA or IIB, depending on which one was operating. A single barrier operated at a time during our evaluations; which barrier was not under our control. Extensive measurements by McInerney et al. (2011) have shown that both barriers produce the same ultimate field strength voltage. Therefore, evaluations in different barriers do not confound the results.

Before the trial began, fish were given 1 min to acclimate to the cage in non-electrified water below the electric barrier. We limited the acclimation period to 1 min to reduce the amount of stress experienced by the fish. Because of the extremely low/no flow conditions, that are characteristic of the CSSC, the fish could not swim against a current within the cage. In static water, the caged fish would probe the edges of the cage and sometimes become restricted to the corners of the cage, which appeared to disorient and stress the fish. Once the boat and cage began moving, the majority of fish would orient to the current and begin swimming normally.

After acclimation, we began recording the fish. When the DIDSON was used, a stop watch was started at the same time as the DIDSON. Times were then recorded when the caged fish passed by nine different observation points (Fig. 2; Table 1). These times were later used by workers to record fish behavior at the designated points. When the camcorder was used, the observation point numbers were announced into the camcorder microphone. These verbal cues were later used in the lab to record fish behavior at the designated points.

Trial evaluations using gizzard shad occurred once during the summer of 2011 when the barrier operating parameters were 0.79 V/cm. All other evaluations occurred at the current operating parameters of 0.91 V/cm. Caged-fish evaluations occurred once during the summer and fall of 2011, and winter 2012 using solely an aluminum-hull boat. In the spring and summer of 2012, caged fish were moved through the electrical barriers using both an aluminum-hull and a fiberglass-hull boat. The trials using both aluminum and fiberglass-hull boats were performed within a two-week period during the spring and summer to reduce temporal variability. Boat speeds were adjusted continuously throughout the trial runs depending on the swimming speed of the fish used (typically 1.6–3.2 km/h). Fish that became incapacitated after moving through the barrier were observed beyond the barriers to assess recovery rate.

Recordings of caged fish were reviewed, separately, by two different individuals. Reviewers could slow down, rewind, and review footage for as long as necessary in order to accurately record data. For the purposes of modeling, the data were dichotomized as either “incapacitation” or “non-incapacitation.” Incapacitation was defined as all movement ceasing and the fish becoming impinged against the downstream end of the cage. Non-incapacitation was assigned if the fish displayed any movement. At each observation point, reviewers recorded data for each fish within the cage (e.g. two incapacitated and three not incapacitated at observation point X). If the two reviewers assigned conflicting incapacitation/non-incapacitation ratios at an observation point, then a third reviewer assigned a ratio. If the third assigned ratio matched one of the previous two, then that ratio was used. Disagreements between reviewers relative to the number of fish completely incapacitated versus exhibiting some movement only accounted for 0.005% of all recorded observations (36/6650 observations). Because the fish did not have unique external tags attached to them, the lengths of the individuals are unknown.

Data analyses

Binary logistic regression was used to estimate the probability of fish incapacitation as a function of distance into the barrier system from our predetermined starting point (Agresti, 2007). Fish that immediately became impinged on the back of the cage when the boat first started moving through non-electrified water, presumably because of previous capture and handling stress, were omitted from analyses. By modeling the binary response of each fish randomly assigned to a treatment (control, mid-channel, west wall), each fish was considered to represent a single Bernoulli trial, or replicate, in which only two outcomes were possible (Breen and Ruetz, 2006; Agresti, 2007; Gotelli and Ellison, 2004). However, if the assumption that each fish represents a Bernoulli trial is not true, slope and intercept estimates would not be affected, yet the probability of a type I error would be inflated (Breen and Ruetz, 2006; Agresti, 2007). The logistic regression analyses that were initially performed on the data collected during the spring using the fiberglass-hull boat had quasi-complete separation of data points (i.e., a specific distance at which all fish went from not being incapacitated to being incapacitated). For convergence and comparative purposes a score of one was artificially added to each observation distance (Allison, 2008).

The modeled distance at which 50% of gizzard shad were incapacitated (median incapacitation distance, hereafter) was estimated from the slope and intercept estimates from each logistic regression function. The median incapacitation distance is the distance at which the estimated odds of incapacitation and non-incapacitation are equal; such that at distances less than this, fish are more likely to not be incapacitated, and at distances greater than this, fish are more likely to be incapacitated. To evaluate the effect of temperature, conductivity, and fish size on median incapacitation distance, a principal components analysis (PCA) was used to reduce the dimensionality of the correlated independent variables into a single value, or principal component (PC) score, for each trial period. This analysis was only performed for the present barrier voltage in which an entire year of data were available. Median incapacitation distances were $\log_{10}$-transformed to homogenize variances and a linear regression was used to examine the relationship between PC1 scores and median incapacitation distances. Pearson correlations between both PC1 and PC2 scores and associated independent variables were performed to assess which variables were most strongly associated with both PC axes. A lack of within-season replication precluded analyses relative to the effects of canal location (canal wall or mid-channel) and boat hull material, so results are described.

Results

Reduced operating parameters (0.79 V/cm)

Of the 270 fish that were pulled through the barrier system, 3% did not become incapacitated ($n = 4$ through the mid-channel and $n = 4$ along the west canal wall). One of the fish that was moved through the mid-channel exhibited erratic swimming, in which it was briefly impinged on the back of the cage (but still moving); the other seven fish swam the entire time while moving through the barriers. Nine percent of the total number of fish used in the trials immediately became incapacitated and were not included in any of the analyses. Because unique identifiers were not attached to the fish, it was impossible to know the lengths of individual fish that traversed the barrier. The estimated slopes and intercepts for the logistic regression models for all run locations were significant ($p < 0.001$) at the lower operating parameters. The logistic regression model for the control runs showed a low probability of fish becoming incapacitated as a result of being forced to swim along a boat while caged and the proportion of variability explained was very low (generalized $R^2 = 0.38$, slope $= -3.69$ [SE $\pm$ 0.36], intercept $= 0.01$ [SE < 0.01]; Fig. 3). The logistic regression models for the mid-channel (generalized $R^2 = 0.74$, slope $= -4.09$ [SE $\pm$ 0.27],

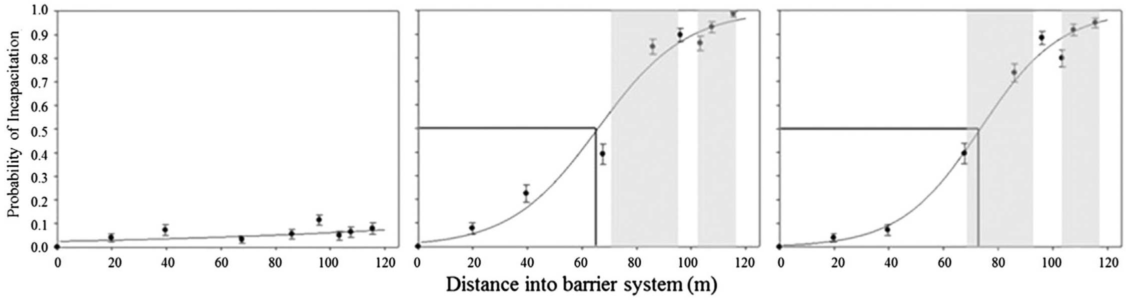

Fig. 3. Predicted incapacitation probabilities of encaged gizzard shad as a function of distance at different locations with the barrier operating at 0.79 V/cm. Left panel is for control section, middle panel is midchannel section and right panel is for wall section. Lines extending from x and y axes denote predicted point at which half of the fish became incapacitated, or median incapacitation distance (mid-channel and west wall only). Filled circles represent the mean (±SE) of incapacitation of observations at specific site distances. Shaded areas represent locations of wide and narrow barrier arrays.

intercept = 0.06 [SE < 0.01]) and west wall (generalized $R^2 = 0.75$, slope = −5.01 [SE ± 0.33], intercept = 0.07 [SE < 0.01]) runs had higher proportions of variability explained relative to the control location given that distance was a better predictor for incapacitation. The median incapacitation distances were 68 m in the mid-channel and 72 m along the west wall; the estimated median incapacitation distance for the control was 369 m, which was far beyond the distance that evaluations were performed (Fig. 3). The average sizes of fish (mm ± SE) used in the control, mid-channel, and canal wall trials were 127 (6), 124 (6), and 111 (3), respectively. The average water conductivity was 0.74 mS/cm (SE < 0.01), and average water temperature was 24.2 °C (SE ± 0.11).

Current operating parameters (0.91 V/cm)

All fish that were moved through the barriers, at the current operating parameters of 0.91 V/cm, were incapacitated at some point. Note that ten percent of the total number of fish used in the trials immediately became incapacitated and were not included in any of the analyses. The probability of incapacitation was strongly related to distance into the electric barrier, as indicated by significant slope values for all but two trials, one of which was a control (Table 2). The distance into the barrier system in which fish became incapacitated varied widely however, depending on season, the location of the canal in which fish were moved through (mid-channel or along west wall), and the type of boat used (fiberglass or aluminum hull) (Fig. 4). Fish that were moved through the barriers in the winter and spring became incapacitated in the shortest distance; whereas during the summer when fish were moved along an aluminum vessel, the fish swam the farthest into the barrier system. During all seasons, fish that were moved through the barrier along the canal wall advanced farther into the barrier before becoming incapacitated than those that were moved through the middle of the canal (Table 2). All fish that were moved through the barrier system recovered in less than one minute post-incapacitation.

The PCA analysis revealed a temperature-conductivity-fish size gradient along the first principal component (PC1), revealed distinct groupings among fish sizes and the two environmental variables between seasons, and explained 72% of the variation among independent variables (Fig. 5; Table 3). The second axis (PC2) explained 24% of the variation and showed a weak fish size gradient (Fig. 5; Table 3). The fish used in the trial runs were largest in the spring and winter when temperatures were lowest and conductivity was highest. The linear regression between PC1 scores and incapacitation distances revealed a significant inverse relationship ($R^2 = -0.60$, p = 0.003; Fig. 6). A separate linear regression was performed between the PC 1 scores and median incapacitation distances of fish used with the aluminum-hull boat; we excluded the fiberglass hull observations that had potentially high

Table 2
Mean conductivities, temperatures, and total lengths of gizzard shad used in trials, median incapacitation distances (distances at which 50% of the fish were estimated to be incapacitated; a dash [–] indicates 50% incapacitation was not achieved), generalized coefficients of determination (R^2) and estimated logistic regression slopes and intercepts under various conditions. Results are only for trial runs that took place at the current barrier operating parameters.

Season	Conductivity (mS/cm ± SE)	Temperature (C ± SE)	Barrier Location	Boat Vessel	Mean fish size (mm ± SE)	Median incapacitation distance (m)	Generalized R^2	Estimated slope (± SE)	Estimated intercept (± SE)
Fall	0.89 (0.01)	12.53 (0.14)	Control	Aluminum	129.5 (1.72)	–	0.33	−3.86 (0.53)*	0.01 (0.01)*
Fall			Mid-channel	Aluminum	130.6 (3.94)	46	0.71	−4.24 (0.38)*	0.09 (0.01)*
Fall			Canal wall	Aluminum	123.6 (2.04)	61	0.73	−5.80 (0.56)	0.10 (0.01)*
Winter	1.16 (<0.01)	9.30 (0.08)	Control	Aluminum	132.8 (2.79)	–	0.54	−3.97 (0.63)*	0.03 (0.01)*
Winter			Mid-channel	Aluminum	132.2 (6.29)	31	0.65	−3.69 (0.84)*	0.12 (0.03)*
Winter			Canal wall	Aluminum	130.7 (2.30)	33	0.66	−3.76 (0.70)*	0.12 (0.02)*
Spring	0.97 (0.01)	15.41 (0.03)	Control	Aluminum	211.6 (1.37)	–	0.38	−4.29 (0.54)*	0.02 (0.01)*
Spring			Mid-channel	Aluminum	212.9 (1.28)	31	0.66	−8.18 (1.56)*	0.27 (0.05)*
Spring			Canal wall	Aluminum	216.8 (1.38)	32	0.66	−5.39 (0.82)*	0.17 (0.02)*
Spring	1.10 (0.01)	15.40 (0.02)	Control	Fiberglass	213.0 (2.67)	–	0.64	−2.27 (0.36)*	0.01 (<0.01)*
Spring			Mid-channel	Fiberglass	224.3 (1.17)	32	0.66	−2.68 (0.38)*	0.09 (0.01)*
Spring			Canal wall	Fiberglass	221.1 (4.15)	36	0.67	−2.52 (0.41)*	0.07 (0.01)*
Summer	0.76 (<0.01)	26.10 (0.21)	Control	Aluminum	115.0 (2.15)	–	0.35	−3.80 (0.64)*	0.01 (0.01)*
Summer			Mid-channel	Aluminum	122.7 (2.38)	76	0.75	−5.41 (0.65)*	0.07 (0.01)*
Summer			Canal wall	Aluminum	118.2 (2.83)	81	0.75	−3.86 (0.47)*	0.05 (0.01)*
Summer	0.67 (0.03)	25.04 (0.08)	Control	Fiberglass	105.8 (1.80)	–	0.60	−2.85 (0.41)*	0.02 (<0.01)*
Summer			Mid-channel	Fiberglass	117.8 (3.39)	41	0.69	−3.21 (0.44)*	0.08 (0.01)*
Summer			Canal wall	Fiberglass	116.0 (2.78)	51	0.72	−3.36 (0.40)*	0.07 (0.01)*

*$P < 0.05$

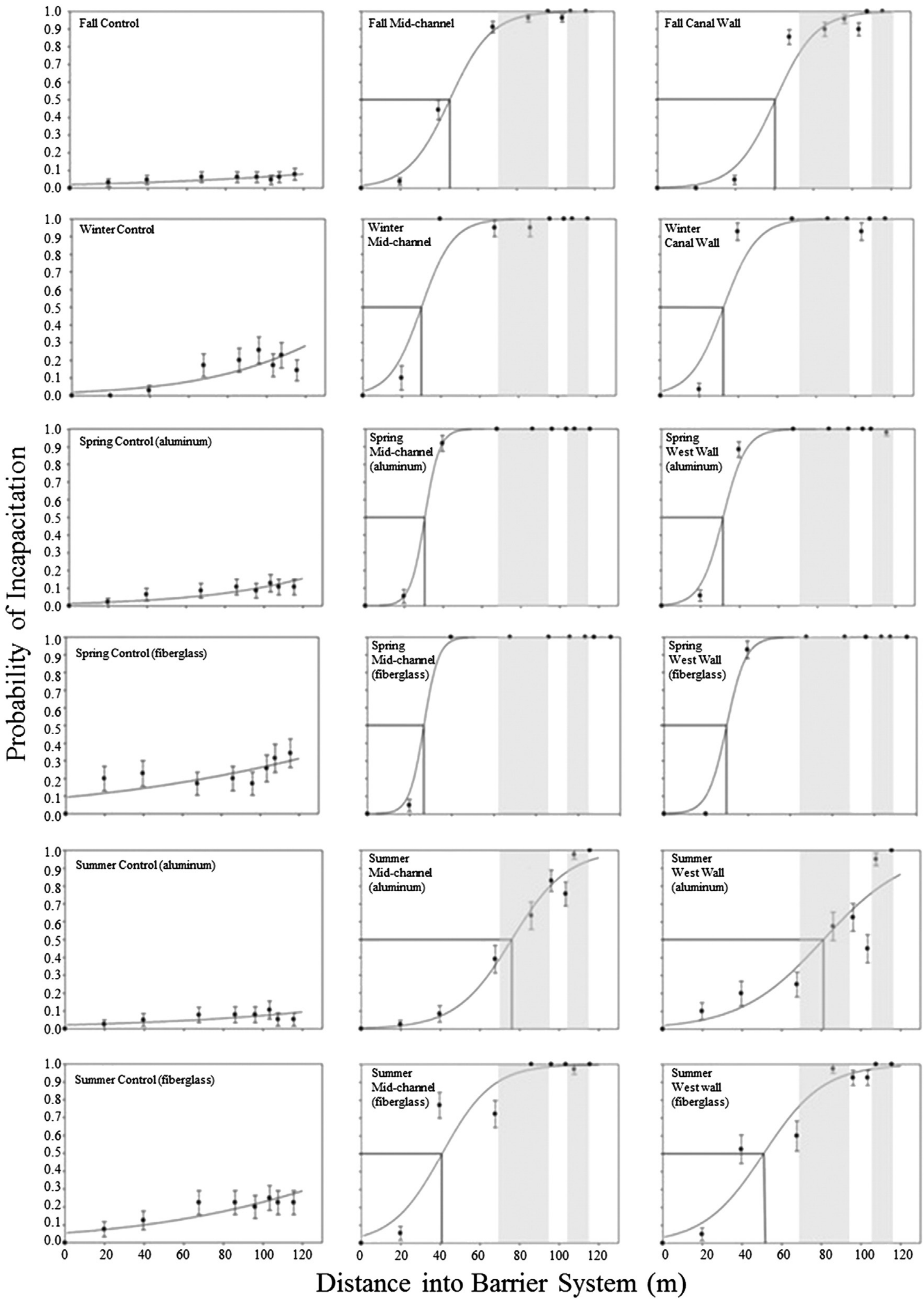

Fig. 4. Predicted incapacitation probabilities of encaged gizzard shad as a function of distance during different seasons and alongside different boat hulls (spring and summer only [during the fall and winter, only aluminum-hull boats were used]) with the barrier operating at 0.91 V/cm. Lines extending from x and y axes denote predicted point at which half of the fish became incapacitated (referred to as median incapacitation distances in later analyses). Filled circles represent the mean (±SE) of incapacitation of observations at specific site distances. Shaded areas represent locations of wide and narrow barrier arrays.

influence on the relationship. The results of the separate regression revealed no uncoupling of the relationship; the correlation became stronger when considering only aluminum-hull boat observations ($R^2 = -0.85$, $p = 0.001$).

Discussion

We found that after barrier operating parameters were increased all fish were incapacitated, which is in contrast to when the barrier was at

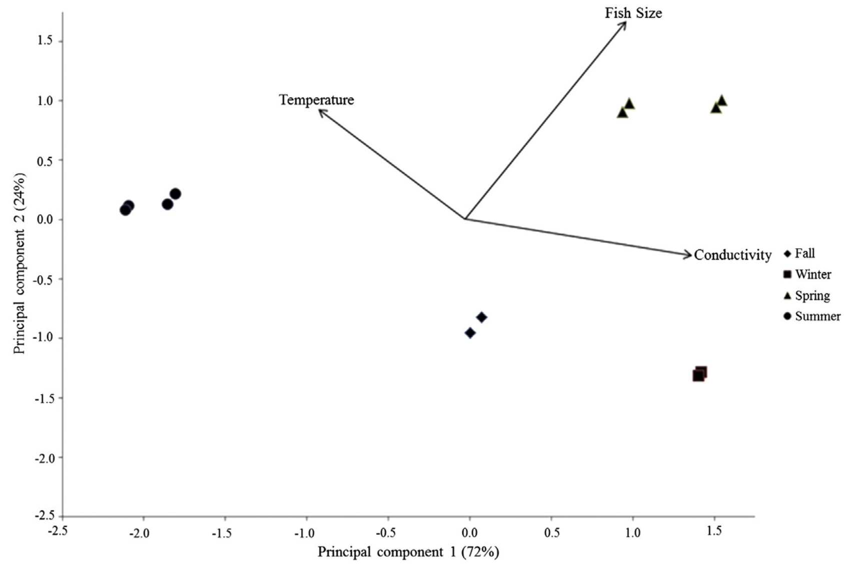

Fig. 5. Principal components analysis bi-plot of three continuous variables measured during trial runs (current operating parameters only). Arrows represent eigenvectors multiplied by two to scale to bi-plot area.

lower operating parameters. Variation in the distance at which the fish became incapacitated at the increased parameters was dependent on a combination of water temperature, fish size, canal location (near wall or mid-channel), and boat material the fish were next to during transport. Incapacitation occurred at shorter distances into the electric barrier with larger fish and cooler temperatures (i.e., spring and winter) relative to the smaller fish and warmer temperatures observed during the summer.

Conductivity in the CSSC is inversely related to temperature as a result of heavy winter road salt application in the city of Chicago (Holliman, 2011). High conductivities normally decrease the effect of electricity on fish (e.g. Reynolds, 1996). However, the cooler temperatures likely compensate for the potential reduction in effectiveness, as evidenced by the shortest incapacitation distances occurring during the highest conductivity observations.

We observed that the fish used in the winter were lethargic and swam very slowly during the trials prior to incapacitation. We suggest that these results offer a line of evidence that the barrier is least susceptible to breach during the winter. Reduced movement and activity of temperate zone fishes during colder months has been well documented (e.g. Gauthreaux, 1980). In the spring, the short distances into the barrier that fish became incapacitated were more likely a result of large fish size than cooler water temperature. Temperatures were higher in the spring than in the fall, yet fish were incapacitated sooner in spring than fall. We used the smallest fish that were available to us for the spring trials. However, the fish were likely age-1 fish from the previous year. Numerous studies relative to the effects of electrofishing have revealed a positive relationship between fish size and electrical effectiveness (e.g. Reynolds, 1996).

Table 3
Correlation matrix between principal component scores and associated environmental variables and fish size.

	Conductivity (mS/cm)	Temperature (C)	Fish size (mm TL)
Principal component 1	0.96*	−0.89*	0.68*
Principal component 2	−0.13	0.42	0.73*
Conductivity (mS/cm)		−0.86*	0.54
Temperature (C)			−0.31

*$P < 0.05$

Caged fish during the summer showed the largest difference resulting from the effect of boat hull material. Although the gizzard shad were of similar size, the fish that were moved along the aluminum-hull boat were able to swim nearly twice the distance into the barrier as those that were moved along the fiberglass-hull boat. Others have found that steel-hulled barges and aluminum boats conduct electricity as they traverse the barrier in the CSSC (Dettmers et al., 2005; McInerney et al., 2011; Slater et al., 2011), which can create voids of non-electrified water in which fish can swim unaffected (Parker and Finney, 2013). We also found that, in all seasons, fish were able to swim into the barrier slightly farther along the canal wall, indicating that the wall may be conducting electricity, and therefore weakening barrier effectiveness as a fish deterrent or for immobilization.

The electric barrier system in the CSSC is the only electric barrier system that also operates in a navigation channel that regularly accommodates large barge vessels, particularly because it serves as the only permanently open connection between the Mississippi River and Great Lakes Basins. Our results have implications for the ability of barge vessels to facilitate fish breach at the barrier system by clearly demonstrating that even our small metal-hulled vessel affected the incapacitation abilities of the barriers. Larger metal-hulled vessels surely will have more profound effects on the electrical field (Parker and Finney, 2013). Besides metal barge hulls distorting the electric field (Dettmers et al., 2005; McInerney et al., 2011; Slater et al., 2011), barges also create a complex suite of hydrodynamic water motions as they navigate through riverine waterways (Bhowmik and Mazumder, 1990; Maynord and Siemsen, 1990; Wolter and Arlinghaus, 2003). The direct (Killgore et al., 2001; Gutreuter et al., 2003; Wolter et al., 2004; Killgore et al., 2011) and indirect (Gutreuter et al., 2003; Kucera-Hirzinger et al., 2009) impacts of tow-barge vessel navigation on fish has been well investigated. However, the actual distances that fish are physically displaced by barges, especially near electrical barriers, is a topic that is currently being investigated more thoroughly. Preliminary results of fish-barge interaction field studies at the barrier system have revealed multiple modes in which barge vessels can facilitate fish breach across the barriers (Parker and Finney, 2013).

Others have shown that fish are indeed entrained by barges and towboats (Gutreuter et al., 2003; Miranda and Killgore 2013), including bighead and silver carps (Killgore et al., 2011). These studies have taken place in large rivers that are very different from the CSSC. Killgore et al.

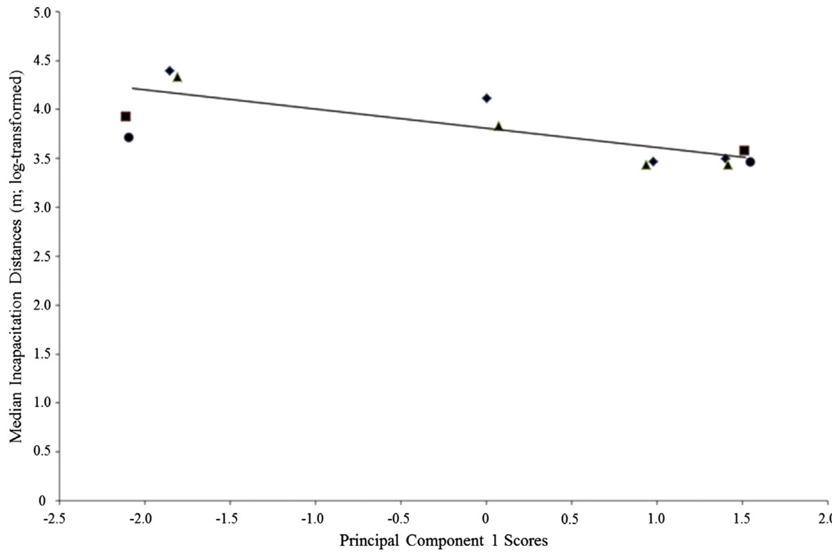

Fig. 6. Regressions of principal component 1 and barrier-run, incapacitation distances (natural-log transformed). Diamonds (◆) denote trial runs along the canal wall with an aluminum-hull boat, squares (■) denote trial runs along the canal wall with a fiberglass-hull boat, triangles (▲) denote trial runs through the mid-channel of the canal with an aluminum-hull boat, and circles (●) denote trial runs through the mid-channel of the canal with a fiberglass boat.

(2011) found though that fish entrainment was high in narrow sections of water with slow velocity in large rivers. Indeed, the electrical barrier system in the CSSC presents a different scenario in which fish encounter a barge vessel than what others have studied. We have found that large numbers of fish will accumulate immediately below the barrier (Parker et al., 2013). The barrier may then act as a "third wall" in the canal system that does not allow fish to escape oncoming barge vessels, thus making them more susceptible to barge-induced water movements.

The farthest-upstream extent of the Illinois River where adult Asian carp can be readily captured using conventional fish-capture gear is about 23 km downstream from the electrical barrier system. However, environmental DNA of bighead and silver carps is regularly detected above the barrier system, leading some to contend that a small population of Asian carp likely resides in the CAWS (Jerde et al., 2011, 2013). The upstream extent of age-0 Asian carp in the Illinois River, which would pose the greatest threat to barrier breach, have been documented at river kilometer 312, which is 164 km, with 5 lock and dam structures, below the barriers (Jeffrey Stewart, USFWS, Per. Obs.). In December 2009, an adult bighead carp was captured below the barriers in the Lockport Pool and, in June 2010, an adult bighead carp was captured in Lake Calumet, which is 48 km upstream of the barrier system (Moy et al., 2010). The discovery of a small number of Asian carp farther away from the larger, established population is consistent with numerous other examples of leptokurtic dispersal patterns, in which a few bold individuals move much farther than the majority of the population (Rehage and Sih, 2004; Roberts and Angermeir, 2007; Breen et al., 2009) including invasive fishes (Jones and Stuart, 2009; Lynch and Mensinger, 2012). Furthermore, invasive species often exhibit lag times from the period in which they are initially introduced to a novel habitat, to when they disperse widely (Williamson, 1996; Crooks and Soulé, 1999; Nico and Fuller, 1999). This dispersal lag time phenomenon was displayed by Asian carp as well prior to invasion of the Illinois River from the Mississippi River (Chick and Pegg, 2001). If Asian carp exhibit the same lag time phenomenon, then a large number could suddenly expand from their current range extent to immediately below the barriers.

We found that after the barrier operating parameters were increased from 0.79 V/cm to 0.91 V/cm that all fish that were moved through the barrier were incapacitated at some point. However, during the summer, small fish were able to penetrate much farther into the barrier system before incapacitation, indicating that during the summer the barrier is probably most susceptible to breach. The summer is also when barge navigation is at its peak in the CSSC, small mobile fishes are most abundant, and fish most aggressively challenge the barrier (Parker et al., 2013, USFWS, unpublished data). The results of this study have raised important questions about the ability of a large barrier to both allow navigation and inhibit the movement of fish. These factors and concerns should be considered by fisheries managers when contemplating the implementation of costly barrier systems.

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